STUDIES OF FINITE AMPLITUDE SHEAR WAVE INSTABILITIES

James T. Kirby
Center for Applied Coastal Research
University of Delaware
Newark, DE 19716
phone: (302) 831-2438, fax: (302) 831-1228, email: kirby@coastal.udel.edu
Award# N00014-94-1-0214

LONG-TERM GOALS

My long-term goal is to develop numerical codes which are applicable to the full range of low-frequency surfzone motions, to test and refine these codes using results from field measurement programs, and to apply these codes to the prediction and characterization of fluid motions and resulting sediment transport and evolution of beach morphology.

OBJECTIVES

The scientific objective of this study is to gain an understanding of various features of the low frequency nearshore current climate, including:

1. The long term evolution and dynamics of shear waves.
2. The effect of interaction and competition between several unstable wavenumber modes of finite amplitude shear waves.
3. The dynamics of edge waves in an environment where the underlying longshore current structure is strongly modified by the presence of shear waves.
4. The effect of organized forcing of the shear waves by the incident waves.

The motions being studied can provide a sizeable portion of the total energy content in inner surfzone motions, and thus have a (presently not understood) impact on sediment transport and the evolution of beach morphology. We seek to eventually address these issues using the information about the hydrodynamic environment obtained from the present study.

APPROACH

We have developed a numerical code with the objective of studying the motions and combinations of motions described above. This code has been used to study the long-time evolution of shear waves over realistic beach topographies with and without longshore bars. We have investigated the relative importance of bottom friction and turbulent and dispersive lateral mixing mechanisms in controlling the growth of shear waves, and we have, in turn, investigated the relative importance of small-scale lateral mixing and shear wave-induced Reynolds stresses in determining the distribution of wave-induced longshore current. The code will be further utilized to investigate the effects on shear wave evolution caused by spatial and temporal inhomogeneity of both driving forces and bottom topography. Finally, the model is being extended to allow for the computation of an evolving bottom.

WORK COMPLETED

A model of the nonlinear shallow water equations with additional bottom friction and forcing terms has been developed. The model is robust and the numerical code has been refined in a number of ways to pursue numerical experiments simulating various types of low frequency motions in the surf zone as well as in the swash zone. The model has been extensively tested and has been applied to the generation of subharmonic edge waves and their growth to finite amplitude (Özkan-Haller and Kirby, 1997a).

The model was used to analyze the dynamics of shear waves in the absence of other low frequency motions. For this purpose we first simulated shear instabilities of the longshore current on a plane beach (Özkan and Kirby, 1995). Studies were also carried out examining if shear instabilities of the longshore current account for the low frequency energy observed at the Superduck experiment (Özkan-Haller and Kirby, 1996). The low frequency climate at Superduck was examined by attempting to identify the combination of bottom friction and mixing coefficients which led to a flow regime that best reproduced the observations (Özkan-Haller and Kirby, 1997b).

RESULTS

Studies of shear instabilities on a plane beach have produced results which are in agreement with independent results by Allen, Newberger and Holman (J. Fluid Mech, 1996) who utilized a rigid lid model. It was shown that the long term evolution of instabilities in the longshore current is strongly dominated by subharmonic transitions. These transitions were analyzed in detail (Özkan-Haller, 1997). We found that the transitions occur in the form of vortex collisions where a weaker vortex structure catches up and collides with a slower more energetic vortex in front of it. During the collision of the vortices, there appears to be an exchange of identities of trailing and leading events, much as in the elastic collision of shallow water solitons. After the collision, most of the energy is transferred to the initially weaker trailing vortex and a subsequent reduction in the number of large vortices is evident. The resulting flow structures are longshore progressive and exhibit strong offshore directed velocities. These results are possibly suggestive of a mechanism for the formation of migrating rip currents. Since it is suspected that rip current motions may be intensified by the distortion to the incident wave field caused by wave-current interaction effects, we are exploring the inclusion of this distortion in the forcing terms in the numerical model.

Several cases using measured bottom bathymetry and wave heights from the Superduck field study have also been studied. Bottom friction as well as momentum mixing due to turbulence and depth variations in the currents are taken into account. A friction coefficient c_f and a mixing coefficient M control the nature of the simulated motions. We deduce a realistic range of values for c_f and M from measurements. Decreasing c_f within that range results in more energetic shear instabilities with higher propagation speeds. At present, we use the predicted propagation speed of shear waves as the criterion for determining a “best” friction coefficient (see Figure 1), and then use the predicted maximum longshore current velocity as a verification of this procedure. The shear instabilities induce significant momentum mixing in the surf zone and alter the mean longshore current profile. The current profile before the instabilities are initiated along with the final mean current profile are shown in Figure 2 for one case at Superduck. Also shown are the measured mean currents. It is observed that the final current profile is not altered by the amount of mixing due to processes other than the instabilities. If more mixing due to turbulence is assumed (higher M), the instabilities are less energetic and the mixing due to the instabilities decreases proportionally to produce the same current profile. In all cases mixing due to the instabilities is seen to dominate over other mixing mechanisms. However, the reason for the apparent balance between the various mixing mechanisms and the resulting insensitive longshore current profile is not understood and deserves further investigation.

Vortex interactions of the type observed for the simpler case of a sloping bottom are also present for the cases involving the barred Superduck bathymetry. Snapshots of the vorticity field (Figure 3) show the complicated nature of the motions. Vortex pairs propagate in the longshore direction y, interact, occasionally merge and are shed offshore.

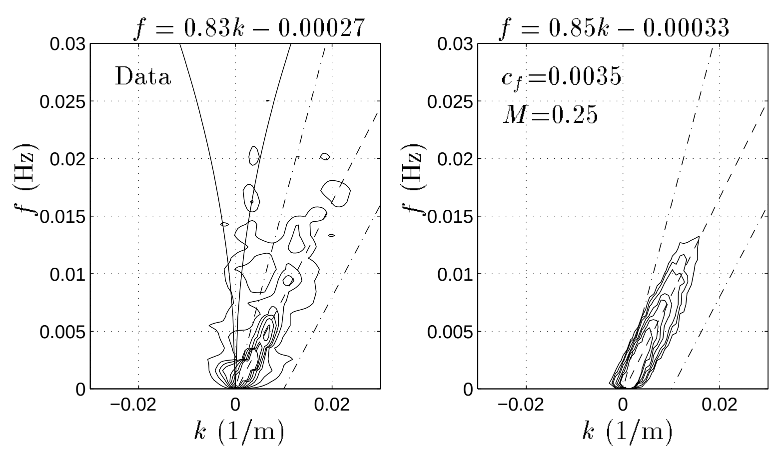

Figure 1: Frequency-cyclic longshore wavenumber spectra $S(f,k)$ ($\mathrm{m^3/s}$) for longshore velocities from measurements on October 16. The equation for the dispersion line (dashed) is noted.

IMPACT/APPLICATIONS

This study has shed light on the processes that are important in the low frequency range of the energy spectrum, such as interactions between low frequency waves and response of the low frequency environment to external forcing. As shear waves have an important effect on the velocity structure around the breaker line they are also a plausible explanation for offshore mixing. As a result of this study the magnitude of this effect can be assessed and the general understanding of nearshore circulation and mixing patterns can be advanced. This study can also serve as a benchmark for other studies that are not restricted to low frequency motions, but where the low frequency motions are embedded in higher frequency oscillations, making the processes difficult to identify.

TRANSITIONS

The model code developed here is being used in an ONR-funded study of the inversion of SAR images of the water surface to determine bottom bathymetry (with R. A. Dalrymple, Delaware), in conjunction with a much more numerically intensive Boussinesq wave model. The model and results also form the basis of further proposed work on edge wave and shear wave interactions (Putrevu, Kirby and Oltman-Shay, NSF) and on the characterization of nearshore motion using coherent structure analysis (Kirby, ONR).

REFERENCES

Özkan, H. T. and Kirby, J. T. 1995. Finite amplitude shear wave instabilities. *Proceedings of Coastal Dynamics 1995*, Gdansk, 465-476.

Özkan-Haller, H. T. and Kirby, J. T. 1996. Numerical study of low frequency surf zone motions. *Proceedings of 25th International Conference on Coastal Engineering*, Orlando, 1361-1374.

Özkan-Haller, H.T. 1997. Nonlinear Evolution of shear instabilities of the longshore current. Ph.D. dissertation, University of Delaware.

Özkan-Haller, H. T. and Kirby, J. T. 1997a. A Fourier-Chebyshev collocation method for the shallow water equations including shoreline runup. *Applied Ocean Research*, 19, 21-34.

Özkan-Haller, H. T. and Kirby, J. T. 1997b. Shear instabilities of longshore currents: Flow characteristics and momentum mixing during Superduck. *Proceedings of Coastal Dynamics 1997*, Plymouth, in press.

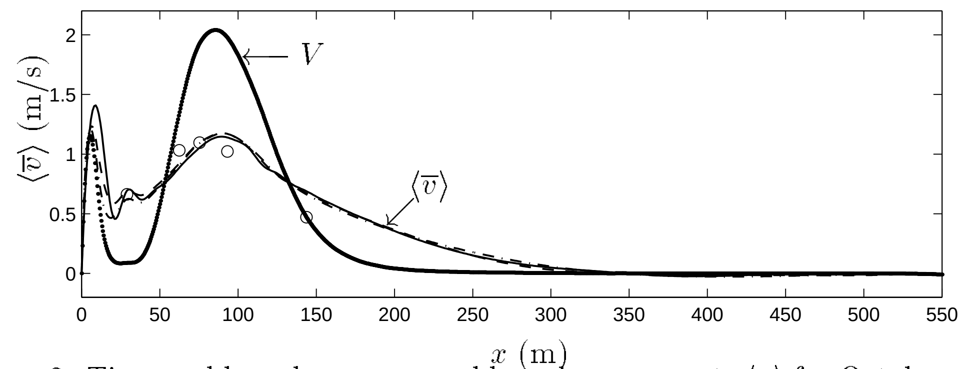

Figure 2: Time and longshore-averaged longshore currents $\langle\overline{v}\rangle$ for October 16 for $c_f = 0.0035$ and $M = 0$ (solid), $M = 0.25$ (dashed), $M = 0.5$ (dash-dotted) and sled data (o). Also shown is the mean current in the absence of shear instabilities V for $c_f = 0.0035$ and $M = 0.5$ (dotted).

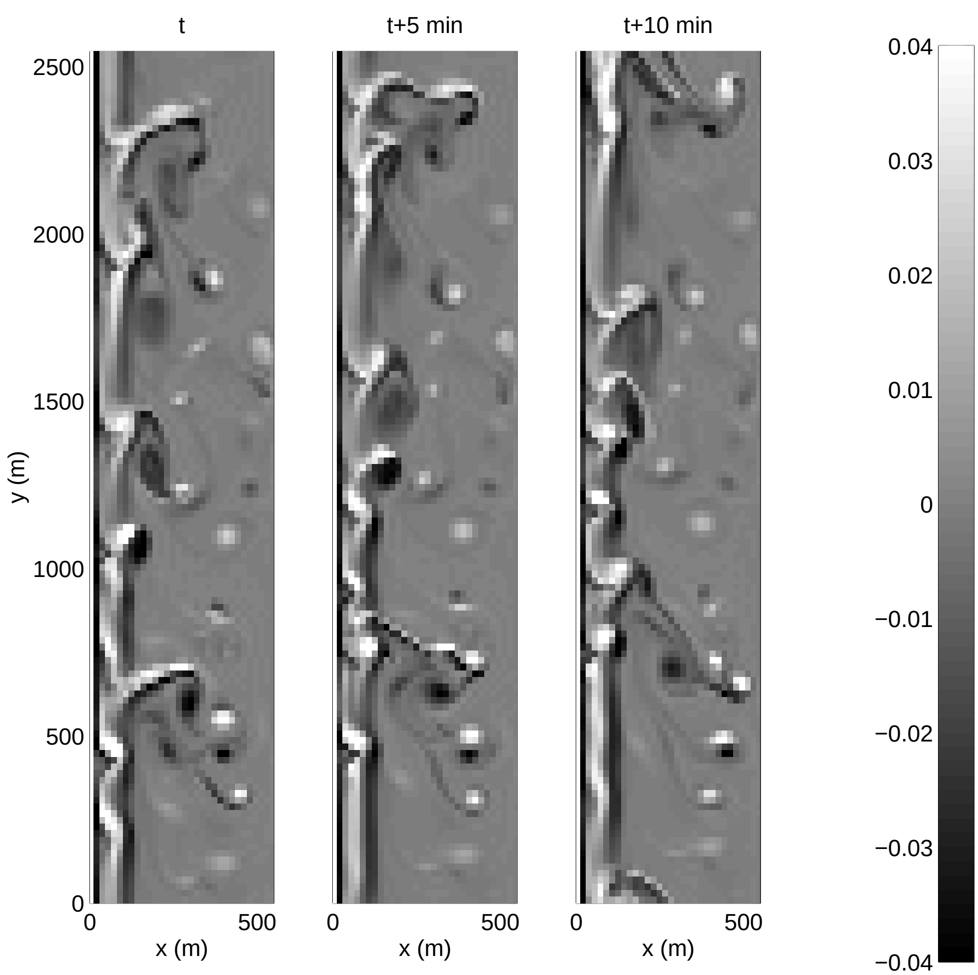

Figure 3: Snapshots of contour plots of vorticity q (1/s) at 5 minute intervals for $c_f = 0.0035$ and M=0.25.